N-body simulations of dissipationless galaxy formation

C. Nipoti* - P. Londrillo** - L. Ciotti*

* Dipartimento di Astronomia, Università di Bologna
** INAF - Osservatorio Astronomico di Bologna

DOI: 10.1388/SSC(2005)-AP-122

ABSTRACT – *Studiamo lo scenario di collasso non dissipativo per la formazione delle galassie, utilizzando simulazioni numeriche ad alta risoluzione realizzate con il codice parallelo per simulazioni a N-corpi FVFPS*[1]. *In accordo con studi precedenti, troviamo che le proprietà strutturali dei prodotti finali delle simulazioni sono consistenti con quelle delle galassie ellittiche reali. In particolare, nelle regioni centrali le distribuzioni finali di densità superficiale sono caratterizzate da* core *piatti, la cui estensione è determinata dal rapporto viriale iniziale.* Core *simili sono osservati nei profili di brillanza superficiale delle galassie ellittiche, cosiddette di tipo "core". Concludiamo che il collasso non dissipativo è un'alternativa plausibile allo scenario dei buchi neri binari come origine dei* core *osservati.*

We study the dissipationless collapse scenario for galaxy formation with the help of high-resolution numerical simulations realized with the parallel N-body code FVFPS[1]. *In accordance with previous studies, we find that the structural properties of the simulation end-products are consistent with those of real elliptical galaxies. In particular, in the central regions the final surface density distributions are characterized by flat cores, whose size is correlated with the initial virial ratio. Similar cores are observed in the surface brightness profiles of the so-called "core" elliptical galaxies. We conclude that dissipationless collapse is a plausible alternative to the binary black hole scenario as origin of the observed cores.*

The dynamical process of dissipationless collapse of a self-gravitating system of particles is relevant to the astrophysical problem of galaxy formation. This process was introduced to describe a complex physical scenario, in which the gas cooling time of the forming galaxy is shorter than its free-fall time, stars form "in flight", and the subsequent dynamical evolution is a dissipationless (and collisionless) collapse. It is now well established that the end-products of dissipationless collapses reproduce several structural and dynamical properties of elliptical galaxies[2]. We studied this

---

[1] P. Londrillo, C. Nipoti, L. Ciotti, In "Computational astrophysics in Italy: methods and tools", Roberto Capuzzo-Dolcetta ed., Mem. S.A.It. Supplement, **1**, p. 18 (2003).

[2] T. S. van Albada, MNRAS, **201**, 939 (1982).

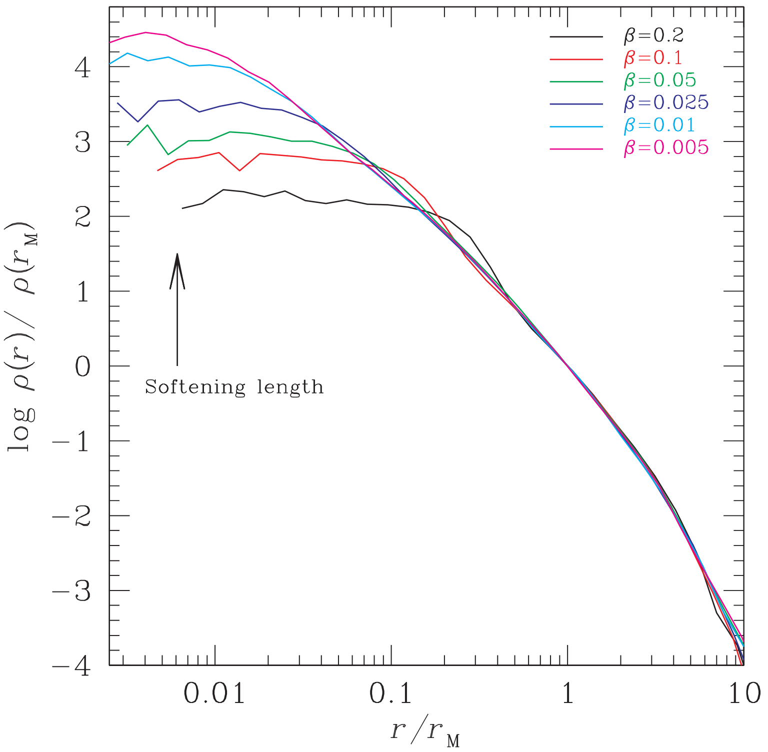

FIGURE 1. – *Angle-averaged density profiles for the end-products of collapses with different initial virial ratios* β.

process using high-resolution N-body simulations, whose results can be compared with the recent high-quality photometry data of elliptical galaxies. A more extended and detailed description of our work is given in [1].

For the simulations we used the parallel $O(N)$ N-body code FVFPS (Fortran Version of a Fast Poisson Solver[1]), based on an algorithm developed by W. Dehnen[3]. The simulations were run on 16 processors of the Linux Cluster IBM CLX/1024 at CINECA. Here we present results from simulations with $N = 409600$ particles. As a test, one of the simulations was rerun with $N = 1024000$ particles, giving results consistent with the corresponding lower-resolution simulation.

The initial conditions are characterized by an (inhomogeneous) density distribution, and by the associated virial ratio $\beta = 2K/U$ (K and U are the initial kinetic energy and the self-gravity of the distribution, respectively). The particles are first distributed according to a smooth, spherically-symmetric Plummer density distribution, and then inhomogeneity is introduced as a perturbation of the smooth distribution. The velocities are randomly extracted from an isotropic Gaussian

---

[3] W. Dehnen, Journal of Computational Physics, **179**, 27 (2002).

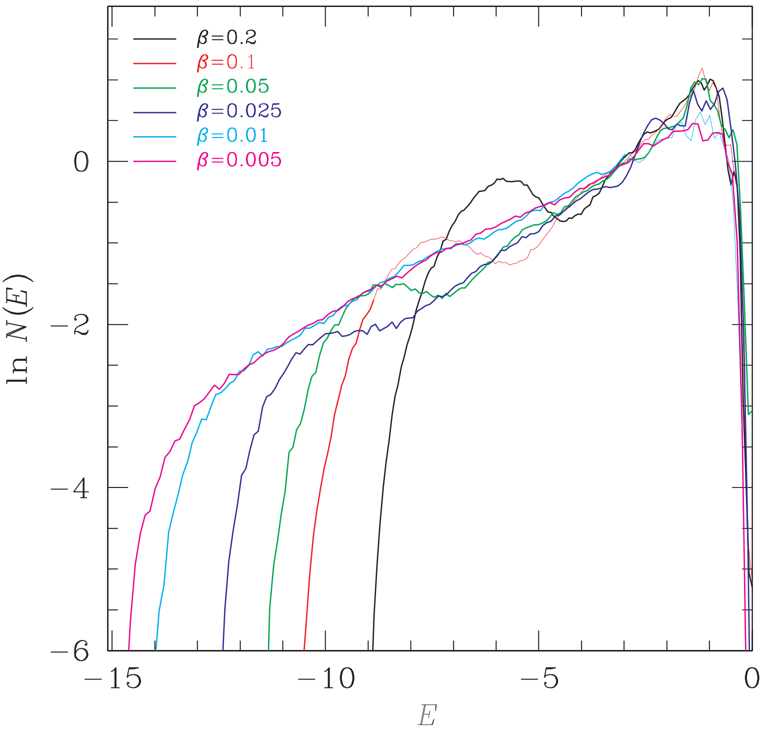

FIGURE 2. – *Differential energy distributions for the same models as in Fig.* 1. *E is normalized to* $|E_{tot}|/M_{tot}$.

distribution and then normalized to obtain the required value of the virial ratio β. All simulations are evolved up to virialization, which is reached typically within $40t_{\rm dyn}$, where $t_{\rm dyn} \equiv GM_{\rm tot}^{5/2}/(-2E_{\rm tot})^{3/2}$ is the dynamical time of the system ($M_{\rm tot}$ and $E_{\rm tot}$ are the total mass and energy). We analyzed the end-products by measuring their angle-averaged density distribution $\rho(r)$ and half-mass radius $r_{\rm M}$, and, for the projections along the principal axes of the inertia ellipsoid, the circularized surface density profile $I(R)$ and effective radius $R_{\rm e}$.

In Fig. 1 we plot the angle-averaged density profiles of the final states of the collapses, for different values of β in the range $0.005-0.2$. All the end-products have remarkably similar density profiles at large radii, while at small radii they are characterized by flat cores, whose size correlates significantly with β. We note that the central flattening is apparent at radii unaffected by artificial numerical effects, which are expected at radii of the order of the softening length (vertical arrow). This result, confirming what found by May & van Albada[4] with lower resolution collapse

---

[4] A. May, T.S. van Albada, MNRAS, **209**, 15 (1984).

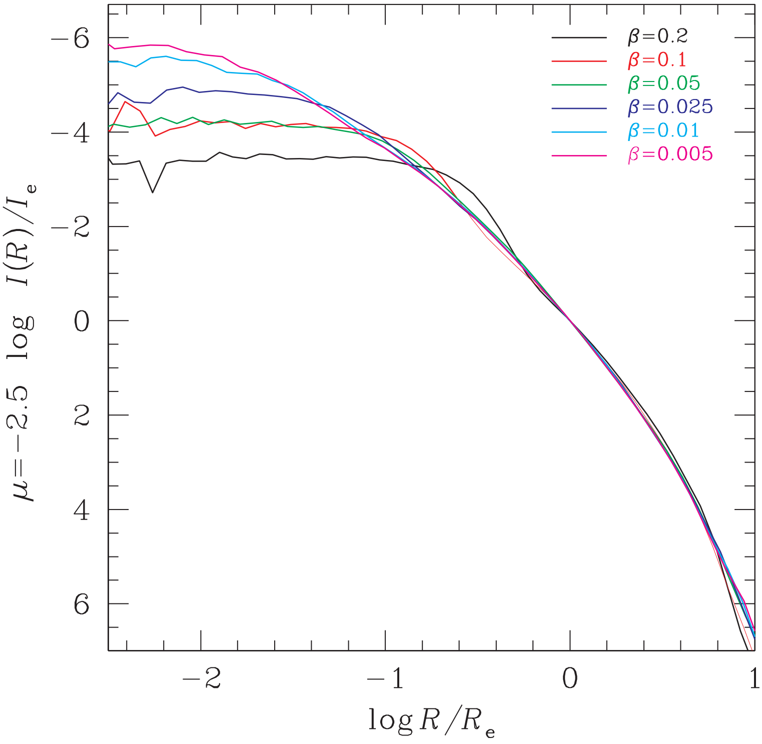

FIGURE 3. – *Circularized surface density profiles for projections along the major principal axis of the same models as in Fig.* 1.

simulations, is a consequence of the Liouville Theorem, stating that phase-space density is conserved along the trajectories in phase-space.

The influence of β on the properties of the end-product is apparent also from Fig. 2, plotting the differential energy distribution $N(E)$ (i.e. the number of particles with energy per unit mass between E and $E + dE$) for the same models as in Fig. 1. For cold enough initial conditions ($\beta \lesssim 0.01$), the final differential energy distribution is well represented by an exponential $N(E) \propto \exp{(\alpha E)}$, over most of the energy range[2, 5]. We find that the colder the initial conditions, the larger the range in E in which $N(E)$ is exponential, because only very cold initial conditions produce strongly bound particles (and, correspondingly, populate the central regions of the end-product). For $\beta \gtrsim 0.1$ $N(E)$ is clearly bimodal.

The curves reported in Fig. 3 show, for the same set of models, the circularized surface density profiles for the projection of the end-products along their major principal axis. In accordance with previous studies[2], the projected profiles of cold enough collapses are well described by the de Vaucouleurs' $R^{1/4}$ law[6] over most of the

---

[5] G. de Vaucouleurs, Ann. d'Astroph., **11**, 247 (1948).

[6] J. Binney, MNRAS, **200**, 951 (1982).

radial range. At radii smaller than a characteristic "break radius" the profile flattens and deviates from an inward extrapolation of the $R^{1/4}$ law. The break radius is smaller for colder initial conditions, and as small as $\sim 0.01R_{\mathrm{e}}$ for $\beta \lesssim 0.01$.

Interestingly, Hubble Space Telescope observations[7, 8], probing the luminosity profiles of several ellipticals down to sub-arcsec resolution, revealed that within $\lesssim 0.01R_{\mathrm{e}}$ the profiles of several (bright) ellipticals are characterized by flat cores, similar to those of our end-products. The presence of a core is usually interpreted as a consequence of merging of supermassive black holes (e.g.[9]). However, our results suggest that the flat inner surface brightness profiles of "core" ellipticals can be naturally produced also by dissipationless collapse without successive mergings. In this picture, the core size is just a signature of the coldness of the protogalaxy.

Publications

[1] C. NIPOTI, P. LONDRILLO, L. CIOTTI, MNRAS, submitted.

---

[7] L. Ferrarese, F.C. van den Bosch, H.C. Ford, W. Jaffe, R.W. O'Connell, AJ, **108**, 1598 (1994).

[8] T. R. Lauer, et al., AJ, **110**, 2622 (1995).

[9] J. Makino, T. Ebisuzaki, ApJ, **465**, 527 (1996).